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Winter cereal production in a Mediterranean silvoarable walnut system in the face of climate change

M. Guadalupe Arenas-Corraliza*, M. Lourdes López-Díaz, Gerardo Moreno

INDEHESA Research Institute, University of Extremadura, Avenida Virgen del Puerto, 2. Plasencia, Cáceres 10600, Spain

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ABSTRACT

One of the foreseeable consequences of climate change is a reduction in crop yields. In recent years, agroforestry systems have been identified as a strategy for climate change mitigation and adaptation. In this study we assess the potential of a silvoarable system to protect crops against extreme climate events. We studied a 9-year-old hybrid walnut silvoarable system (*Juglans x intermedia Mj209xRa*) intercropped with cultivars of two winter cereals – wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) – for three consecutive years and compared it with monocrops and pure tree plantations. The parameters studied were grain and total biomass yield, harvest index, grain size and tree diameter increment. Plant phenology and soil and plant nutrients were also examined. Climate conditions and tree presence conditioned cereal yields, and the responses to silvoarable conditions differed among cereal species and cultivars. The silvoarable system with barley had higher production than monocrops in years with early heat events (yield increment of 55% in the first year and 15% in the second year). For wheat, no positive effect of trees in the silvoarable system was found, although grain quality improved significantly (2.56% and 2.76% N grain content in monocrops and silvoarable systems, respectively). Tree growth, measured as diameter at breast height increment, was lower in the silvoarable system (2.06 cm at the end of the study) than in the monospecific plantation (2.83 cm in the same period). The land equivalent ratio was always higher than 1 (1.34–2.08), showing that the silvoarable system was more productive than sole pure plantations and cereal monocrops.

1. Introduction

World population growth in the second half of the 20th century required an increase in crop yield that was achieved by improved agronomic techniques and seeds. However, despite the need to double food production in the 21st century to feed the increasing human population, yields have stagnated in recent years (Tilman et al., 2002) as a result of climate change and recurrent extreme weather events such as heat waves and prolonged drought (Ray et al., 2012). In the coming years, global wheat yield is likely to decrease by 6% for each degree-Celsius increment in mean temperature (Zhao et al., 2017). Any increase in arable land is expected to be insufficient to provide enough food for the rising human population this century (Alexandratos and Bruinsma, 2012), requiring the design of more productive and more sustainable systems. Many approaches have been suggested to achieve advances in ecological intensification, which aims to increase the yields of land through better use of its resources (Bommarco et al., 2013).

Agroforestry systems, defined as integrated land-use systems, are among these ecological intensification approaches (Tittonell, 2014). Agroforestry is the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal production systems to benefit from the resulting ecological and economic interactions (Burgess et al., 2015). Many studies (e.g., Schoeneberger et al., 2012) have reported that trees help to regulate the climate beneath them by reducing temperature extremes, providing shelter from the wind and limiting soil surface evaporation. In Mediterranean areas, trees can stabilise grass production through the typical inter-and intra-annual rainfall variation (Gea-Izquierdo et al., 2009; Joffre and Rambal, 1993; Moreno, 2008). Woodland shade also limits water loss by crop transpiration, thus increasing the water use efficiency of the system, a key factor in adapting to climate change (Lasco et al., 2014). The role of integrated systems as a climate change adaptation mechanism has recently been recognised by the European Conference on Rural Development (EU, 2016), the European Strategy for Climate Change (EU, 2014), the European Forestry Strategy (EU, 2013) and the latest International Panel on Climate Change report (Fifth Report) (IPCC, 2015).

Silvoarable systems producing trees and crops are one of the possible combinations within agroforestry systems. The species used,

* Corresponding author.
E-mail address: garenascorraliza@unex.es (M.G. Arenas-Corraliza).

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wheat and walnut, are two of the most commonly studied species in temperate silvoarable systems (Wolz and DeLucia, 2018). Trees appear to have the ability to extend roots to deeper layers when there is competition in the shallower layer, which could help to ensure sufficient belowground resource acquisition (nutrients and water) and adequate growth rates (Andrianarisoa et al., 2015; Cardinael et al., 2015). Crop response to conditions imposed by trees under the Mediterranean climate and other water-limited regions remains uncertain (van der Werf et al., 2007). While some studies have identified plant traits that could be beneficial in certain wheat cultivars to withstand partial shade caused by pollution in some areas (Li et al., 2010), interest has recently increased in studying how shade generated by trees affects wheat yield (Dufour et al., 2013; Mu et al., 2010). However, these studies have overlooked how barley, characterised by its drought tolerance (Xia et al., 2017), could respond differently from other cereals in silvoarable systems.

This study attempts to shed light on the production of winter cereals and timber trees in a silvoarable system in a Mediterranean area in years with contrasting climate conditions. In this area, high inter-annual rainfall variations and spring heat waves are becoming common, agreeing with foreseen future climate scenarios (Gerald and Tebaldi, 2004; Giorgi and Lionello, 2008; Trnka et al., 2014). We compared the productivity of different cultivars of barley and wheat cultivated in open fields and under 9-year-old hybrid walnuts. Our specific hypotheses were:

(i) *There is competition between crops and trees that negatively affects crop yield*. This hypothesis was assessed by comparing crop yield (and soil and plant nutrients) between silvoarable vs cereal monocrops in years with no specific climatic constraint.
(ii) *During spring heat waves, winter cereals could be more productive under trees*. Crop yield was compared between silvoarable and monocrops in years with spring heat waves.
(iii) *Crop yield under silvoarable conditions depends strongly on the crop species and cultivars*. Comparisons of phenology and crop yield among silvoarable and monocrops were performed for species and cultivars differing in precocity.
(iv) *Grain quality could differ between the silvoarable combination and monocrops*. Nutrient content of barley and wheat grains produced in monocrops and silvoarable plots were compared.
(v) *Tree growth diminishes in the silvoarable system*. Stem growth was compared between trees in silvoarable and forestry plots. Leaf nutrients were also compared.

Lastly, we evaluated the overall yields of the study systems by calculating the land equivalent ratio (Mead and Willey, 1980) over three years to determine whether the silvoarable system is more productive than forestry and monocrops in the face of climate change.

The experiment is part of the European project AGFORWARD, which aims to promote agroforestry systems in Europe through proposals for innovation and social recognition of their environmental services. This study helps to identify crops adapted to silvoarable systems under a Mediterranean climate.

2. Material and methods

2.1. Study site

The experiment was conducted from 2013 to 2016 in a hybrid walnut plantation in central-western Spain (Toledo, Spain; coordinates ETRS89 39° 50′ 54″N 4° 28′ 2″W, 411m a.s.l). The climate of the region is Mediterranean, with hot dry summers and cool rainy winters. Average annual temperature and rainfall are 15.2 °C and 439 mm, respectively. Drought usually occurs from June to September. The soil is Fluvisol, with a depth of more than 1.4 m. Initial soil analysis indicated a sandy loam texture with an acidic pH in the upper 20 cm (pH 6 in water) (Table A1 in Supplementary material), making the area suitable for cultivating the species used in the study.

The study was carried out in a 9-year-old (in 2013) hybrid walnut plantation, planted in former cereal fields at 6 m between-row and 5 m within-row spacing (333 trees ha^{-1}). Before 2013, the whole plantation had been treated with herbicides in tree rows and ploughed in alleys to keep it weed free. In the study period, canopy closure was almost complete and trees were pruned each year before and during the study. At the beginning of the experiment, mean tree height and diameter at breast height (DBH) were 10.5 m and 15.3 cm, respectively. Every summer (July–September), trees were irrigated at the same rate in the silvoarable and forestry systems using a drip irrigation system, with a total amount of 2000 $m^3\ ha^{-1}$ and water quality adequate for walnut irrigation (Table A2 in Supplementary material). The nutrient content applied to trees through irrigation in summer was 40 kg N ha^{-1}, 17.5 kg P ha^{-1} and 41.5 kg K ha^{-1}. The plantation was certified by the Forest Stewardship Council (FSC). The woodland was a clone of Nat7 of hybrid walnut *Juglans x intermedia Mj209xR*a, resulting from pollination of *Juglans major* Torr. *var. 209 (Mj209)* with *Juglans regia* L. *(Ra)*. This hybrid is known for its fast growth (hybrid vigour) and low fruit yield, and has considerable capacity to adapt to different soils and warm areas of the Iberian Peninsula. Walnut buds usually break after mid-April. A large adjoining area without trees that had previously been cultivated with winter cereals (wheat and barley) was used for the monocrop system.

2.2. Experimental layout

Three vegetation systems were compared: intercropping of cereals in walnut plantation alleys ("silvoarable"), cereals grown in open fields ("monocrops") and pure tree plantation without intercropping ("forestry"). Silvoarable and forestry plots were adjacent to each other, in the same walnut plantation area (Fig. A1 in Supplementary material). Trees in the silvoarable and forestry plots had received similar management before the study and were similar in size. The systems were established at a distance from each other (Fig. A1 in Supplementary material) because it was a private plantation that did not allow a randomised block design. However, to ensure that soil conditions were similar between treatments, soil properties were evaluated and no apparent differences were detected for the more common parameters (Table A1 in Supplementary material).

For the silvoarable treatment, six plots measuring 120 m^2 (20 m long × 6 m wide, including 5 trees in each line and cropped alleys 4 m wide) were cultivated and located randomly per cultivar of cereal. Six 2 × 2 m plots were established per cereal variety without trees as a control for cereal production (monocrops), spaced 0.5 m apart (Fig. A2 in Supplementary material). The forestry control comprised three plots of trees without cereals (45 trees per plot). The location of the plots varied across the three years. Cereal species were carefully sown by hand spreading in early November each year in the silvoarable and monocrop systems. Soil was prepared by harrowing in June and again a few days before sowing. All cereal plots were fertilised in November (just before sowing) with 48 kg ha^{-1} N, 31 kg ha^{-1} P and 60 kg ha^{-1} K and in February (cereal tillering) with 55 kg ha^{-1} N.

The winter cereal species were barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.). The sowing rate was 180 kg ha^{-1} for barley and 220 kg ha^{-1} for wheat. The selected cultivars varied over the years depending on seed availability but were the same each year in the monocrop and silvoarable systems. Barley cultivars were Doña Pepa and Azara in 2013, Basic, Lukhas, Hispanic and Dulcinea in 2014 and Meseta and Hispanic in 2015. Wheat cultivars were Kilopondio and Bologna in 2013, Ingenio, Sublim and Nogal in 2014 and Ingenio, Nogal, Botticelli and Idalgo in 2015. All of these cultivars are commonly sown in Spain in Mediterranean areas because of their proven adaptation to drought and high temperatures.

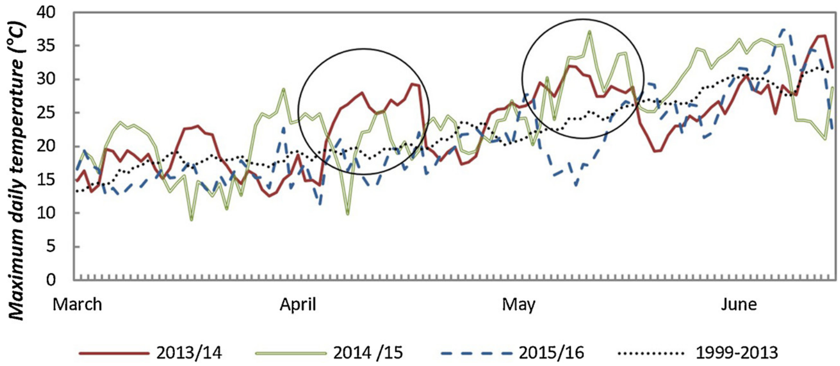

Fig. 1. Maximum daily temperatures (°C) during 2013/14, 2014/15 and 2015/16 growing seasons and mean value for the period 1999–2013.
Source: Based on data from *Vegas de San Antonio* weather station.

2.3. Weather conditions

Climate data was obtained from Vegas de San Antonio weather station (coordinates ETRS 89 39° 57′ 21″N and 4° 42′ 1″W), 18 km from the plot but at the same altitude in a flat region. The annual precipitations (Fig. A3 in Supplementary material) of the growing seasons studied (2013–2014, 2014–2015 and 2015–2016), at 387 mm, 284 mm and 302.2 mm, respectively, were lower than the 1999–2013 average (442 mm). Spring rainfall in the third year was almost triple that of the first year and twice that of the second year (Fig. A3 in Supplementary material). Major differences also occurred in winter: in the first year, winter rainfall was almost 60% of total rainfall (229 mm), whereas in the second and third years it was 15% and 20%, respectively (Fig. A3 in Supplementary material). One notable occurrence was a long period with high temperatures in April and May in the first and second years, when flowering had already started in the cereals (Fig. 1), but in the third year no heat waves occurred and temperatures were lower than in the previous years.

2.4. Field measurements and sampling

Cereal phenology was recorded in 16 plants per plot on three dates in 2016 (May 4, May 26, June 7) by Zadoks growth stages (Zadoks et al., 1974). Once cereal plants had matured, samples were harvested using hand clippers in June 2014, 2015 and 2016 at ground level in 50 × 50 cm squares, taking three samples per plot in the centre of the silvoarable system and two samples per plot in monocrops. Plants were dried at 60 °C to constant weight. The variables measured to determine cereal yield were total aerial biomass weight, total grain weight and weight of 1000 grains. The harvest index was calculated as the ratio between grain weight and total aerial biomass weight.

Tree DBH was measured using a diameter tape every year in the dormant period (January) in 180 trees in the silvoarable system (four central trees per plot) and 45 trees in the forestry system.

Tree leaves were sampled in July 2014, 2015 and 2016 after randomly selecting 12 trees in each treatment (forestry and silvoarable). In each tree, two shoots were cut in the middle of the crown in all directions (N, S, E, W) using telescopic shears. Terminal leaflets were collected from leaves in the middle of the shoot, stored in paper bags and dried at 60 °C to constant weight. In early June each year, during cereal ripening, five random soil samples at 20 cm depth were taken from each plot and dried at 60 °C to constant weight until analysis in the laboratory.

2.5. Chemical analyses

Plant samples were treated by acid digestion in Kjeldahl tubes in a Gerhardt Block-Digestion Unit, Model 20, for further determination of P and K content. Phosphorus content was analysed using the ISO 15681-2:2003 method with a Seal Analytical AA1 AutoAnalyzer. Potassium content was analysed using a Sherwood Flame Photometer, Model 410, following the ISO 9964-2:1993 method. Cereal grain and tree leaf N content was determined by combustion analysis using the Dumas method (ISO 16634-1:2008) in two replicated analyses per sample with an elemental analyser (DUMATHERM®, Gerhardt). The factor used to convert N content to protein in cereal grains was 5.83.

Soil samples were sieved to < 2 mm and soil was extracted with 1 M KCl to analyse ammonium (NH_4^+) and nitrate (NO_3^-) content (Rayment and Lyons, 2011). Extractions were performed with Melich 1 (Sims, 2000) to determine available P and K. Ammonium content was analysed using the ISO 14256-2: 2005 method in an AutoAnalyzer (Seal Analytical, model AA1). Nitrate was analysed using the same method including a Cd column. Phosphorus and K were determined following the methods ISO 15681-2:2003 and ISO 9964-2:1993, respectively.

2.6. Data analysis

Land equivalent ratio was calculated for grain yield of barley and wheat following Mead and Willey (1980), using the allometric equation developed by López-Díaz et al. (2017) for *Juglans* species to calculate tree biomass.

Differences for mean values in the parameters grain and biomass yield, harvest index, and weight of 1000 grains were analysed by full-factorial ANOVAs, with three fixed factors (year, species and system) and cultivars as a random factor, nested in year and species (Table A3 in Supplementary material). Similarly, growth stages in 2016 were compared with one ANOVA per date, with species and system as fixed factors and cultivars as a random factor. Soil N, K and P were compared for the three systems (monocrop, silvoarable and forestry) by one-way ANOVAs. Differences between systems for N and K content in grains in 2016 were determined by ANOVAs, with system and species as fixed factors and cultivar as a random factor. Differences between systems in 2016 for stem diameter increment and N, P and K content in walnut leaf were determined by *t*-tests. Where ANOVA yielded statistically significant differences ($p < 0.05$), the least squares difference (LSD) test was used for subsequent pair-wise comparisons. All analyses were performed using STATISTICA software (StatSoft Inc., Maison-Alfort, France).

3. Results

3.1. Cereal growth and yield

Grain yield differed between years, species and systems. In the first two years (2014 and 2015), barley grain yield increased in the silvoarable system (Fig. 2). The increment was greater in the first year, at 50% more than in monocrops ($p = 0.008$, Table 1), and less significant in the second year ($p = 0.025$), and was more pronounced in the second

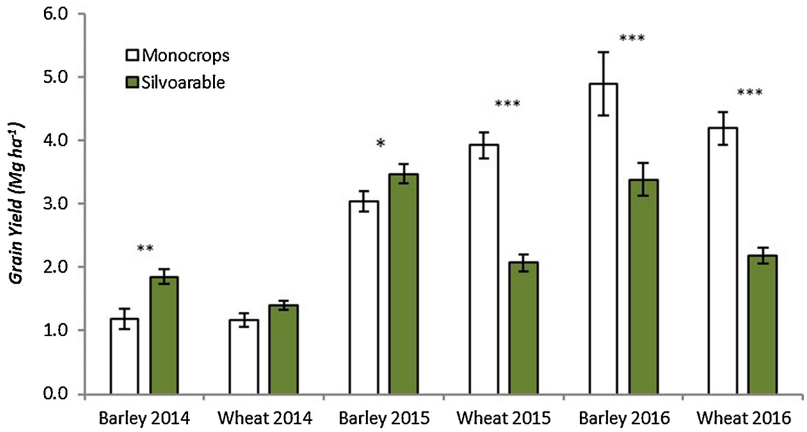

Fig. 2. Grain yield (Mg ha^{-1} ± S.E.) in wheat and barley in the study years in monocrops and silvoarable systems. Significance level: * *p < 0.05; ** p < 0.01; *** p < 0.001.*

year in the Basic cultivar (p = 0.024, Table A4 in Supplementary material).

For wheat, the silvoarable system showed no significant differences in grain yields in the first year. In the second year, yields were significantly lower in silvoarable, with 2.07 Mg ha^{-1} compared to 3.9 Mg ha^{-1} in the monocrop system ($p < 0.001$, Fig. 2), especially in the Sublim and Nogal cultivars ($p < 0.001$, Table A4 in Supplementary material). In the third year, the silvoarable system produced significantly less grain in barley ($p < 0.001$) and wheat ($p < 0.001$) (Fig. 2), showing significant differences for the Hispanic barley cultivar ($p < 0.001$) and the Ingenio, Botticelli, Nogal and Idalgo wheat cultivars ($p < 0.001$, Table A4 in Supplementary material).

Plant biomass was greater in the silvoarable system in barley in the first and second years (p = 0.008 and p = 0.004, respectively, Table 1), especially for the Hispanic cultivar in the second year (p = 0.001, Table A4 in Supplementary material), but showed no difference for wheat. In the third year, when climate conditions were more favourable for cereal plants, monocrops had a higher biomass yield in both species ($p < 0.001$, Table 1), in all cultivars (Ingenio, Botticelli, Nogal, Idalgo, Meseta and Hispanic, $p < 0.001$, Table A4 in Supplementary material). The harvest index in silvoarable system for barley was significantly lower in the second year (p = 0.01, Table 1), especially in the Hispanic ($p < 0.001$), Basic and Dulcinea (p = 0.03 and p = 0.02, respectively) cultivars (Table A4 in Supplementary material). The harvest index for wheat was also significantly lower in the silvoarable system in the second year ($p < 0.001$, Table 1), especially in the Ingenio (p = 0.02), Sublim and Nogal cultivars ($p < 0.001$), as shown in Table A4 in Supplementary material. Wheat grain size (weight of 1000 grains) was greater in monocrops than in the silvoarable system in the first year (p = 0.03, Table 1), especially in the Kilopondio cultivar (p = 0.004, Table A4 in Supplementary material). In contrast, barley grain size was significantly different between systems in the second year ($p < 0.001$), with a higher value in silvoarable (40.61 g) than in monocrops (31.11 g), especially in the Basic (p = 0.003), Lukhas (p = 0.017) and Hispanic (p = 0.043) cultivars, as shown in Table A4 in Supplementary material.

3.2. Crop phenology

Crop phenology was monitored from May 4 (just before walnut leafing) to June 7 (just after walnut leaf and cereal grain maturation). By tree leafing, crops had reached the stage of milk grain development (Zadoks growth stages 70–79), although barley was more advanced than wheat and its growth was faster in silvoarable than in monocrops (Fig. 3). At more advanced growth, during stages 80–89 (dough development) and 90 (ripening), barley grain development was slightly slower in silvoarable than in monocrops. However, there was no difference between systems for wheat development during the milk and dough stages, although ripening was delayed in both wheat and barley in the silvoarable system.

3.3. Grain nutrient content

Wheat N and K content were significantly higher (p = 0.006 and $p < 0.001$, Fig. 4). in silvoarable than in monocrops (6% and 28%, respectively). However, barley showed no significant difference in N or K and tended to be lower in N in silvoarable.

3.4. Tree growth

Tree growth in terms of DBH was monitored in the study years. Trees in the forestry system grew faster than trees intercropped with cereal (Fig. 5). The increment was 100% greater in forestry than in silvoarable in the first year and 20% greater in the second and third years.

Table 1
Biomass yield (Mg ha^{-1} ± S.E.), harvest index and weight of 1000 grains (g ± *S.E.)* of wheat and barley in the study years in monocrops and silvoarable systems. Significance level (*t*-test): * *p < 0.05; ** p < 0.01; *** p < 0.001.*

Year	Species	Biomass yield (Mg ha^{-1})		Harvest index		Weight of 1000 grains (g)	
		Monocrops	Silvoarable	Monocrops	Silvoarable	Monocrops	Silvoarable
2014	Barley	6.32 ± 0.36	7.71 ± 0.27 **	0.19 ± 0.02	0.24 ± 0.01	29.78 ± 1.01	29.62 ± 0.64
	Wheat	8.23 ± 0.26	8.29 ± 0.29	0.14 ± 0.01	0.17 ± 0.01	24.82 ± 1.16	22.34 ± 0.66 *
2015	Barley	5.52 ± 0.22	6.72 ± 0.29 **	0.57 ± 0.03	0.52 ± 0.01*	31.11 ± 2.22	40.61 ± 0.75 ***
	Wheat	6.83 ± 0.16	7.18 ± 0.32	0.57 ± 0.03	0.28 ± 0.01 ***	26.25 ± 2.57	25.82 ± 0.99
2016	Barley	11.58 ± 0.87	7.94 ± 0.33 ***	0.42 ± 0.02	0.42 ± 0.03	26.30 ± 0.96	25.71 ± 0.91
	Wheat	17.10 ± 0.53	8.79 ± 0.40 ***	0.24 ± 0.01	0.25 ± 0.01	21.42 ± 0.80	20.57 ± 0.54

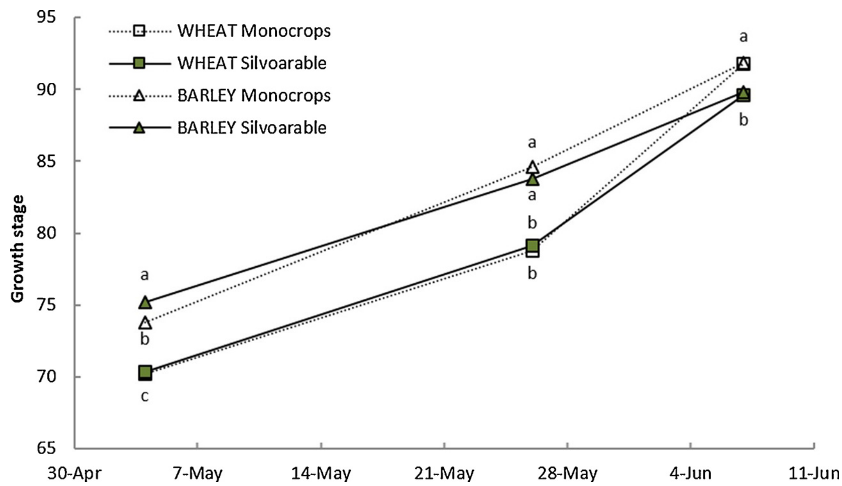

Fig. 3. Growth stages according to Zadoks et al. (1974) of wheat and barley in 2015–2016. Different letters indicate significant differences for the same period. Tree leafing occurred about the first fortnight of May.

3.5. Land equivalent ratio (LER)

Land equivalent ratio for both barley and wheat was > 1 in all years of study. The range was from 1.34 to 2.08 and LER was greater for barley every year (Table 2).

3.6. Walnut leaf nutrient content

Walnut leaf N (mean value of 22.16 ± 0.51 mg g^{-1}) and P (mean value of 1.34 ± 0.11 mg g^{-1}) contents showed no significant differences between systems or years of study. In contrast, walnut leaf K content (Fig. 6) was significantly lower ($p < 0.001$) in silvoarable (13.33 mg g^{-1} in 2015 and 19.15 mg g^{-1} in 2016) than in forestry.

3.7. Soil resources

Soil K content values were higher in monocrops (172 ± 29 mg kg^{-1}), followed by forestry (146 ± 7 mg kg^{-1}) then silvoarable (132 ± 4 mg kg^{-1}), with a significant difference between monocrops and silvoarable ($p = 0.008$). Differences in mineral N (mean value of 22.16 ± 0.51 mg g^{-1}) and available P (mean value of 1.62 mg g^{-1}) were not significant (data not shown).

4. Discussion

4.1. Cereal yield is reduced by trees under a favourable climate for the crop

Cereal biomass and grain production are strongly related to water availability during plant development. Water stress during cereal

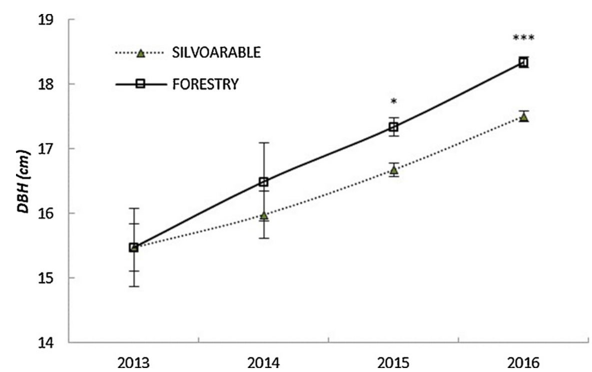

Fig. 5. Means of *Diameter at Breast Height* (DBH) (cm ± S.E.) of *Juglans x intermedia Mj209xRa* in forestry and silvoarable systems in 2013, 2014, 2015 and 2016 study years. Significance level (*t*-test): * $p < 0.05$; *** $p < 0.001$.

Table 2
Land equivalent ratio (LER) of wheat and barley in silvoarable combination with walnut in three study years. Parentheses contain the relative yields of crop grain and tree biomass, respectively.

Year	Tree age (years)	LER	
		Barley + Walnut	*Wheat + Walnut*
2014	10	2.08 (1.55 + 0.52)	1.72 (1.20 + 0.52)
2015	11	1.96 (1.15 + 0.81)	1.34 (0.53 + 0.81)
2016	12	1.55 (0.69 + 0.87)	1.39 (0.52 + 0.87)

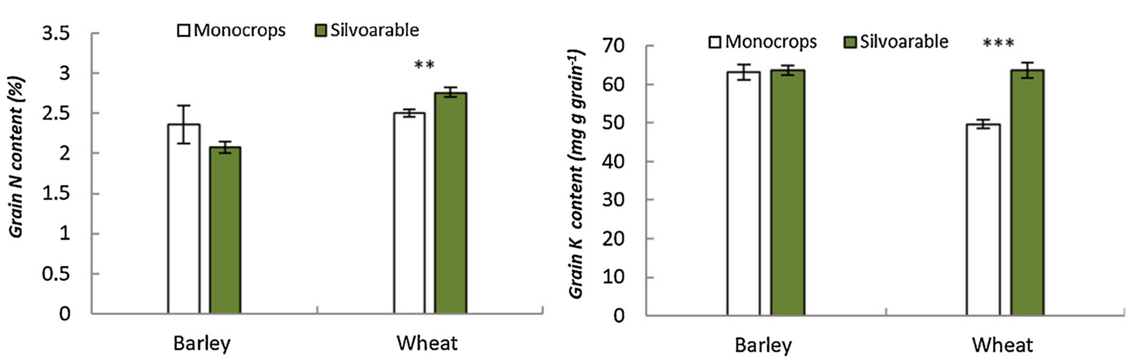

Fig. 4. Grain N (% N ± S.E.) and K (mg g $grain^{-1}$ ± S.E) content of barley and wheat in monocrops and silvoarable systems in 2016. Significance level (*t*-test): ** $p < 0.01$; *** $p < 0.001$.

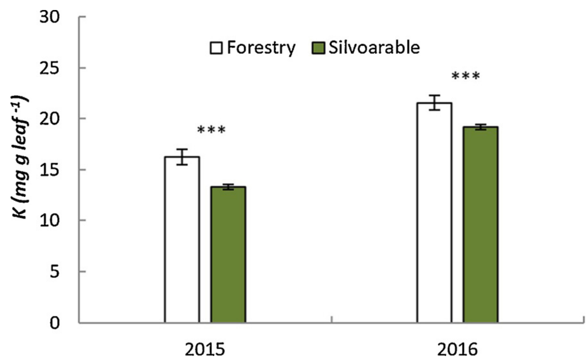

Fig. 6. Walnut leaf K content (mg g leaf^{-1} ± S.E.) in wheat and barley in 2015 and 2016 in monocrops and silvoarable systems. Significance level (*t*-test): *** $p < 0.001$.

tillering reduces the number of shoots (Passioura and Angus, 2010). However, most of the biomass grows in the first part of the vegetative cycle, especially during winter, when water deficit is less frequent. Thus grain yield is largely determined by the biomass assimilated in the last part of the cycle (Asseng and Savin, 2012), corresponding to late spring in our study area. A higher grain yield is therefore foreseeable in years with adequate rainfall in spring, as observed in 2015 and 2016. This is more important for grain formation than total annual precipitation.

In very favourable climate conditions for grain production, as in 2016, trees were detrimental to cereal plants, and grain yield was lower in silvoarable than in monocrops, as reported in previous studies of wheat combined with walnut (Dufour et al., 2013; He et al., 2012; Li et al., 2008), probably due to competition for resources such as light, water and nutrients between the two strata in agroforestry systems (Mead et al., 2010).

Water and nutrient absorption by winter cereals continues after leafing of deciduous trees in Mediterranean silvoarable systems (Dufour et al., 2013). The walnut root system can adapt to soil moisture conditions in silvoarable systems by absorbing more water in deeper layers. However, this cannot prevent competition in shallow layers, where most of the fine roots of the two strata are present, and therefore cereal yield is reduced (He et al., 2012; Zhang et al., 2015). The results showed K competition between the two strata, indicated by K content in the soil, walnut leaves and cereal grains. In cereals, K absorption takes place mainly during biomass production and peaks during flowering, when it starts to be transferred to the grain until ripening (Karlen et al., 1988). When walnuts started budburst in April (when wheat and barley were flowering), they began to consume K for their vegetative requirements. This competition for K seems to be essential to grain yield and nutritional value.

When climate conditions were favourable, biomass and grain yield of both cereals were lower in the silvoarable system due to light reduction and K (and presumably water) competition. Given our lack of a randomised block design, this result could be affected by initial soil differences between the silvoarable and monocrop plots. The change in crop yields in silvoarable, from higher to lower than monocrops under trees depending on the year (see next section) and species, indicates that differences in yields were more dependent on tree-crop interactions and species than on hidden differences in soil properties.

4.2. *Trees protect crops against heat waves*

Cereal biomass in both species and barley grain production were higher in the silvoarable system in the first two years, when heat waves occurred in April and May.

The climate in the Mediterranean area is characterised by considerable inter- and intra-annual differences in precipitation. Extreme weather events, such as spring heat waves and droughts, are increasingly more frequent and therefore a decline in grain yield is expected (Ray et al., 2012). High temperatures post-flowering (grain filling) and low water availability have traditionally been the most frequent causes of abiotic stress in winter cereals, causing reductions in yield (Sadras, 2007). In our study, grain yield values for the two unfavourable years were within the common Mediterranean range of 1–3 t ha^{-1} (Asseng and Savin, 2012).

Cereal production beneath trees could be an effective strategy to mitigate the effects of spring heat waves. Trees are known to have a buffer effect on maximum and minimum temperatures in Mediterranean environments (Gea-Izquierdo et al., 2009) and can reduce the desiccant effect of wind, even before leafing. They bring temperatures closer to the optimum in the first stages of the cereal cycle, when plants produce most of their dry matter between tillering and flowering, helping to keep cereal grain yields high. Moreover, translocation of available carbohydrates to grain is constrained above 25 °C (Romero and German, 2001), which greatly reduces grain yields.

4.3. *Cereal species and cultivars respond differently to silvoarable combination*

Cereal yield in the silvoarable system is related to shade tolerance and the influence of trees at different developmental stages. Wheat is known to be a full-light plant, but in barley, the inclination angle of the leaves and foliage structure allow greater interception of solar radiation (Muurinen and Peltonen-Sainio, 2006). This decreases evapotranspiration and makes plants more tolerant to drought in the ripening stage (Setter and Waters, 2003). As a result, barley has a greater yield under drought stress and is less sensitive than wheat to the possible negative effects of tree shading and soil water competition.

Grain filling in both cereal species is limited by their growth capacity rather than by metabolite accumulation and distribution (Acreche and Slafer, 2006). Stress before flowering can affect carpel growth by decreasing the size of the ovaries (which form the fruit pericarp), reducing potential grain weight regardless of conditions during grain filling (Calderini et al., 2001). Barley flowers and forms grains earlier than wheat (Fig. 3), which decreases the risk of harm from early heat waves and droughts at these critical stages. In dry Mediterranean conditions, barley is prioritised over other cereals (López-Bellido, 1992) because its precocity and rapid ripening have advantages in water use by avoiding the common terminal water stresses.

The silvoarable system slightly increased the speed of barley development until the stage of milk development and delayed the last stages of dough development in both cereals, thus delaying crop maturation. Therefore, in addition to being more premature and having a faster ripening and a shorter grain filling period than wheat (Cossani et al., 2009), barley was in a more advanced phase of grain filling when the walnut trees developed leaves and therefore suffered less water and nutrient competition from trees.

The silvoarable system was beneficial for the harvest index of barley in the first year, when the weather was less favourable, because this ratio is related to high efficiency in the use of resources by crops to increase grain yield (Kumudini et al., 2001). Barley grain yield also increased in the silvoarable system in the second year, indicating that trees are beneficial to barley under a wider range of climate conditions than for wheat. However, the cultivars of each species responded differently. In some cultivars the biomass was more affected and in others the impact was greater on grain number or size. This provides an opportunity to explore which plant traits are affected and favour or hamper productivity in silvoarable systems.

4.4. *Grain quality improves in the silvoarable system*

Barley and wheat grain size and weight are important for industrial applications. Grain filling depends partly on nitrogenous compounds, most of which are accumulated during preanthesis before moving into the grains in postanthesis (Bertheloot et al., 2008). Barley is more

efficient than wheat in translocating these compounds to the grain (Delogu et al., 1998), explaining the higher grain weight in barley than in wheat throughout the study period.

Barley tended to have a lower N content in silvoarable than in monocrops (protein content of 12.09% and 13.75%, respectively, although it should not exceed 12% for malting purposes). This was probably caused by environmental conditions during grain filling (e.g., high temperatures), traditionally considered a cause of malting quality variation (Henry, 1990). This situation could be buffered in the silvoarable system. In contrast, wheat grain N content was enhanced by tree presence and was 10% higher in silvoarable than in monocrops, as reported by Dufour et al. (2013). High N content improves the quality of wheat for use as animal feed, pasta and flour for human intake.

Wheat grain K content was also significantly higher in silvoarable than in monocrops, which may be related to the synergistic relationship between N and K (Carvalho et al., 2016).

4.5. Tree growth is reduced by crops in silvoarable combination

Walnut water requirements are high, at more than 700 mm annual rainfall and as much as 1000–1200 mm in intensive plantations. The study area has an average annual rainfall of 437 mm and is irrigated in summer for normal tree development (60 l $\text{tree}^{-1}\,\text{d}^{-1}$). Even with the same summer irrigation, walnut trees grew less in silvoarable than in forestry. Zhang et al. (2015) reported similar results in a walnut and wheat silvoarable system, mostly explained by competition for resources such as water. Water competition between the two strata begins in winter, because winter cereals consume a portion of the available soil water from winter precipitation. This competition continues from mid spring to early summer (cereal ripening), presumably causing lower available water content for trees in silvoarable than in forestry (Dupraz and Liagre, 2008).

Nitrogen and P levels in walnut leaves showed no difference between systems (forestry and silvoarable). Quantitatively, N is the most important nutrient in walnut. It is needed throughout the growth period because it is essential for tissue formation (Luna, 1990). Phosphorous interacts strongly with N and is especially important for root formation. Remarkably, no competition was observed, indicating that crop and walnut requirements for these two important nutrients are met by the same fertiliser.

However, a major difference was observed in walnut leaf K content between systems. The lower content in silvoarable could explain the greater DBH increment in trees in forestry than in silvoarable, compared to the similar growth in trees in silvoarable and forestry before silvoarable management (Fig. 5). Potassium is the second most important element (quantitatively) in walnut nutrition, because it favours carbohydrate synthesis (Luna, 1990). The considerable K competition between crops and trees should therefore be reduced to ensure adequate timber production.

4.6. Overall yield of silvoarable system in Mediterranean conditions

The silvoarable system presented LER $>$ 1 for barley and wheat in all study years, indicating that the overall yield of the silvoarable system is more positive than the yield of sole cereal crops and trees.

The LER of the silvoarable system was higher than that reported by other authors for the combination of walnut and wheat (Duan et al., 2017; Graves et al., 2007; Zhang et al., 2015), which is partly explained by the climate constraints observed in two of the three years. Although tree effects on the crops varied between years, it was positive (especially for barley) in the years with extreme weather events such as high spring temperatures, which are expected to be more frequent in the coming years as a consequence of climate change in Mediterranean areas (Gerald and Tebaldi, 2004; Giorgi and Lionello, 2008; Trnka et al., 2014).

Using the RCP 4.5 climate change scenario generated with the climate model KNMI-RACMO22E (van Meijgaard et al., 2012) accessed through CliPick (Palma, 2017) for the study site, more than 57% of the years from 2020 to 2050 will have maximum temperatures above 25 °C in the second fortnight of April, affecting barley anthesis and grain filling (Romero and German, 2001). Similarly, more than 80% of these years will have such temperatures in the first fortnight of May, affecting wheat in the same way. Therefore, it seems evident that under the current climate change scenario in Mediterranean conditions, trees can increase winter cereal yields. Although this could cause a decrease in tree growth, silvoarable systems will increase their overall yield because the increase in grain crop production will outweigh the reduction in tree biomass, ensuring more productive and more efficient land use.

5. Conclusion

Combinations of winter cereals and late-bursting walnuts can increase grain yield and LER over monocrops and pure plantations under the current climate change scenario. In very productive years with no climate constraints, cereal yields were significantly reduced by competition with trees in the silvoarable system. In contrast, in years with dry/hot climate events in spring that constrained cereal maturation, tree sheltering acted as a safeguard. In this case yields were higher in silvoarable and the sheltering appeared to be more positive for barley, a more premature and drought resistant crop, than for wheat, although responses depended on the cultivar. Grain quality also improved in the silvoarable combination, especially for wheat.

Crops negatively affected tree growth in the silvoarable system. The competitive use of K among trees and cereal plants revealed in the study should be taken into account to design a specific fertilisation plan in silvoarable systems of winter cereals and walnut under Mediterranean conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2018.05.024.

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